ICE AND FROZEN EARTH AS CONSTRUCTION MATERIALS

by

S. Shyam Sunder
Associate Professor of Civil Engineering
Doherty Professor in Ocean Utilization

(To be published in: Cahn R, (ed.) <u>Advances in Materials Science and Engineering</u>; and Moavenzadeh F, (ed.) <u>Concise Encyclopedia of Building Materials</u>)

November 1987

Department of Civil Engineering
Massachusetts Institute of Technology
77 Massachusetts Avenue, Room 1-274
Cambridge, Massachusetts 02139

Telephone: (617)253-7118
Telefax: (617)253-8000

S. Shyam Sunder, Contract No: 16158A2

ICE AND FROZEN EARTH AS CONSTRUCTION MATERIALS

The cold regions of the world, characterized by the presence of ice and frozen earth, are centered around the poles and extend to about the 40th parallel in both the Northern and Southern Hemispheres. Ice covers between nine and 15 percent of the earth's surface during the year, while nearly one-fifth of all land surface of the earth is underlain by perennially frozen earth or permafrost. The polar zone consists of continuous masses of perennial ice and frozen earth, while the subpolar zone consists of discontinuous or broken masses of ice and frozen earth, both perennial and seasonal in nature. The temperate zone consists mainly of seasonal ice and frozen earth. However, earth frozen in situ by artificial cooling is often used to create retaining structures such as cofferdams for subsurface excavations.

Development and construction, particularly in the polar and extreme subpolar zones, require innovative engineering solutions. Transportation of personnel, materials and equipment, as well as communications pose complex and expensive logistical problems. The environmental impact of development on people and wildlife is a problem of public concern. These problems have been compounded in recent years by the rapid pace of development imposed by society's needs for exploiting scarce natural resources and for maintaining the security of soverign nations.

The ability to work with ice and frozen earth as construction materials is central to cold regions engineering. Both materials are plentiful in supply and inexpensive. Specialized knowledge concerning their many unique mechanical and thermal characteristics is essential for developing safe and economical, yet innovative, engineering solutions. Examples of innovations in recent decades include the development of:

(a) ice roads and bridges and landing strips for aircraft;
(b) ice platforms/islands for working space offshore;

(c) ice barriers for protecting offshore structures from moving ice;
(d) small embankment dams built with permafrost;
(e) large dams and dams in warm permafrost built with thaw-stable and artificially thawed soil;
(f) constructed facilities with passive and active methods for controlling the thermal regime of frozen earth in foundations; and
(g) artificially frozen ground for retaining water and soil during the excavation of tunnels, shafts, etc.

1. Structure and Forms of Ice

Ice can be either a naturally occurring or an "engineered" construction material. Naturally occurring ice is found in many forms and varying morphology, e.g., as river and lake ice, ice islands, glacier ice, icebergs, ground ice, as well as sea ice sheets, floes and ridges. Engineered ice may be formed either by controlled flooding of an area and waiting for the water to freeze, or by spraying water into freezing air so that the vapor instantly crystallizes and falls back to accumulate as a sheet or mound. In certain applications, such as in the construction of ice roads, natural ice may be strengthened by compaction and by additives such as wood shavings and sawdust.

Naturally occurring and engineered ice are generally crystalline in nature. Crystalline ice is known to possess ten polymorphic forms or stable structures under differing temperature and pressure conditions (Fig. 1). The most prevalent form is Ice-Ih, which has a hexagonal lattice structure (Fig. 2). The oxygen atoms are all concentrated along basal planes that are perpendicular to the principal hexagonal axis, called the c-axis. The H_2O molecule consists of an oxygen atom covalently bonded to two hydrogen atoms. Each H_2O molecule is hydrogen-bonded to four other molecules in an approximately tetrahedral coordination.

Grain boundaries develop when growing ice crystals intermingle and achieve an equilibrium configuration (associated with a minimum in surface energy.) Grain sizes are typically in the 1-20mm range, although much larger sizes can exist. During the growth and formation of ice masses, the crystals may be granular, columnar, or in one of many, generally, less important forms. The c-axes of different crystals in an ice mass can exhibit various degrees of alignment, thereby imparting a definite crystallographic texture or fabric to the solid (Fig. 3).

Ice crystals reject impurities such as gas bubbles, salts and organic or inorganic matter during the freezing process. However, large amounts of impurities get trapped within the ice, especially when freezing is fast. Consequently, most ice has a porous structure. In fresh-water ice, the impurities tend to concentrate along grain boundaries together with a thin water film. In salt-water ice, on the other hand, the brine is mostly contained in platelets or cells within the ice crystals and normal to the c-axis. The platelets, with typical spacings of 0.1 to 1.0 mm, impart a cellular substructure to the material. Gravitational forces cause the formation of large tubular brine drainage channels in natural sea ice features. Typically, the brine channels have a diameter of 10 mm and a spacing of 200 mm.

2. Structure and Forms of Frozen Earth

The thermal regime of earth in cold regions depends on its surface temperature (both past and present), thermal properties, type of surface cover, and the geothermal gradient (Fig. 4). At the top there is the active layer in permafrost areas (or seasonal frost layer in other areas), typically extending down from 5 to 15 m, where seasonal freezing and thawing occurs.

Below the active layer, the temperature increases steadily under the influence of heat generated deep in the earth. This heat flows upward at a rate dependent on the geothermal gradient, typically 1 to 5°C per 100m, and achieves equilibrium with the mean ground surface temperature. At the base of the active layer, the earth is either thawed or may include a layer of permafrost. Sometimes, layers of unfrozen ground (e.g., unfrozen cohesive soil versus frozen granular soil) may exist within the permafrost or between the active layer and permafrost (Fig. 5). The thickness of permafrost ranges from a few centimeters at the edge of the subpolar zone to about 60-600 m at the boundary with the polar zone. The thickness of the permafrost layer can reach several hundreds of meters in the polar zone. Ice wedge polygons, ice lenses and other frost features may be present in permafrost regions. The wedges form due to the infiltration of water into cracks which are formed by thermal contraction and expansion of the frozen earth. Such cracks can endure as long as there is no thawing.

Frozen earth is a multiphase material consisting of solid mineral particles, gaseous inclusions (vapors and gases), liquid (unfrozen and strongly bound) water, and ice inclusions. The presence of the new solid phase, the formation of new interfaces, and the random occurrance of air bubbles greatly increase the complexity of this particulate system compared to unfrozen soil. Ice is the distinguishing and important component of frozen earth and may exist both in the form of pore ice which bonds the mineral particles and in the form of large crystals and lenses. The frozen pore moisture is termed ice-cement. Ice-cement bonds depend on many factors, including the degree of negative temperature, the total volume content of ice, the structure and coarseness of ice inclusions, the amount of unfrozen water and the type of soil, i.e., gravel, sand, silt or clay.

If freezing is rapid, ice formation tends to occur only in the pores and is characterized by a fairly uniform distribution. This type of ice imparts a fused or massive cryogenic texture to frozen earth. If freezing is slower in the finer grained soils soils (i.e., silty and clayey soil types), continuous ice interlayers and lenses can form which additionally impart laminar and cellular textures to frozen earth.

Unfrozen water, which depending on the type of soil may be present in frozen earth at temperatures down to about -70°C, generally exists in two states: (a) water strongly bonded by the surfaces of the mineral particles that cannot crystallize even at very low temperatures due to the electromolecular forces of the surface of the mineral grains; and (b) loosely bound water of variable-phase composition, between the layer of bound water and free water, that starts to freeze at temperatures below the normal freezing point (0°C for fresh water). The unfrozen water separates the ice from the mineral grains in frozen earth (Fig. 6). The amount of unfrozen water in frozen earth decreases as the temperature falls below 0°C (Fig. 7). Depending on the unfrozen water content, frozen earth can be classified as either hard-frozen or plastic-frozen. Hard-frozen earth is firmly cemented by pore ice and contains very little unfrozen water (e.g., sands and gravel). In most cases this occurs at temperatures below -0.3° to -1.5°C, although for certain very fine mineral particles the limit can be as low as -5° to -7°C. Plastic-frozen earth, which occurs at higher temperatures, has a larger unfrozen water content, e.g., may be as much as half the total pore water (e.g., silty and clayey soils).

3. Structure-Property Considerations for Ice

The structure of polycrystalline ice governs its macroscopic behavior, both when used as a construction material and when present as an important constituent of frozen earth.

The hexagonal lattice structure of single ice crystals makes ice an intrinsically anisotropic material. Single ice crystals are transversely isotropic (also called cross-anisotropic) because of their hexagonal symmetry. Five independent constants are necessary to characterize their elastic behavior. In spite of its open hexagonal structure, the H_2O molecules are relatively close packed in the basal plane. Consequently, ice crystals deform (slip) easily, and may also crack, between basal planes when subjected to shear stresses. The resistance against deformation and cracking is much higher on other planes.

The behavior of polycrystalline ice is complicated by the presence of grain boundaries and by the degree of grain alignment or orientation. Grain boundaries can impede dislocation slip (i.e., the movement of line defects in a crystal lattice) and cause them to pile-up. Since grain boundary planes are weakened by the concentration of impurities during freezing and the resulting increase in defect density, intergranular sliding (i.e., relative movement between grain boundary planes) may occur in polycrystalline ice. In addition, stress concentrations can cause crack nucleation at irregularities in the grain boundary and at grain boundary junctions, also called triple points.

The degree of grain alignment can be expressed in terms of the relative orientation of the c-axis of different ice crystals. If the c-axes of the different crystals are randomly oriented, the resulting ice is isotropic. On the other hand if the c-axes lie along a plane but are randomly oriented, the resulting ice is transversely isotropic. If the c-axes are all aligned in one direction, the resulting ice is anisotropic. The latter two types of mechanical behavior represent texture or material anisotropy.

Ice is generally very close to its melting temperature in construction applications, i.e., it occurs at a homologous temperature (ratio of ambient to melting temperature in Kelvin) greater than about 0.8. The mechanical behavior of crystalline solids at such temperatures (and even considerably lower temperatures) is controlled by thermally activated rate processes. Thus, ice behavior is very sensitive to rate of loading and temperature variations.

4. Deformation and Failure of Ice

The deformation and progressive failure behavior of ice is governed by three primary mechanisms: flow, distributed cracking, and localized cracking. In particular, ice may display purely ductile, purely brittle or combined behavior depending upon the temperature and conditions of loading. The primary mechanism associated with <u>flow</u> and the constitutive framework of rate theory are appropriate for characterizing purely ductile behavior. The primary mechanism associated with <u>distributed cracking</u> and the constitutive framework of damage theory are appropriate for characterizing deformations during ductile-to-brittle transition or when the material is purely brittle. Such deformations are accompanied by the formation and stable growth of multiple cracks and/or voids. The primary mechanism associated with localized cracking and fracture mechanics theory are appropriate for predicting the failure strength at the onset of material instability.

The effect of the evolution of material structure (e.g., work-hardening) on the macroscopic flow behavior of polycrystalline ice is only beginning to be understood at the present time. There is general agreement, based on theoretical and experimental work, that at least two thermally activated deformation systems, a "soft" system and a "hard" system, must be present for flow to occur. They may be (a) grain boundary sliding (with diffusional accommodation) and basal slip, or (b) basal slip and slip on a non-basal plane. A combination of these processes could be present as well.

Initially, the ice resists the applied stresses in an elastic manner and then flow begins on the soft and hard systems. However, flow, particularly on the "easy" soft system, causes the build-up of internal elastic stresses. This may occur as a result of grain boundary sliding next to grains poorly aligned for deformation or dislocation pile-ups at the boundaries of such grains. Dislocation pile-ups at grain boundaries have been observed in ice through scanning electron microscopy. These internal elastic stresses are known as back or rest stresses. In addition, internal drag stresses which resist dislocation movement and grain boundary sliding are generated by (a) creep resistant substructures, e.g., subgrains and cells, formed by grain boundary sliding or dislocation movement, and (b) dislocation entanglement, dipole formation and kink band formation during slip (particularly on the basal plane.)

An increasing back stress contributes to kinematic hardening which induces directionally dependent material behavior, referred to as deformation induced anisotropy. The Bauschinger effect in metals is an example of kinematic hardening. On the other hand, an increasing drag stress contributes to isotropic hardening. In isotropic hardening, subsequent material properties are independent of the direction of pre-straining.

The deformations resulting from the interactions between the soft and hard systems can be decomposed into two components; a transient flow component and a steady state flow component (Fig. 8). Isotropic and kinematic hardening phenomena are active during transient flow and give rise to elastic strains which are recoverable upon unloading. These time-dependent elastic strains represent delayed elasticity, also called anelasticity. Steady state flow is associated with viscous (irrecoverable) strains which are irrecoverabe. Such viscous deformation is attibuted to intragranular deformation processes, especially to the movement of dislocations. When transient flow has become saturated, hardening effectively ceases and pure viscous flow results. The time-temperature equivalence for both deformation systems is given by the Arrhenius law, with similar activation energies for each system.

As the rate of deformation is increased, flow is accompanied by crack formation in initially crack free ice. Sudden changes in temperature, i.e, thermal shocks, can also induce cracking. Less is known about cracking in ice than is known about its flow behavior. Cracks generally tend to nucleate in regions of high defect density, which for polycrystalline fresh water ice occur at grain boundaries. Elastic stress concentrations are severe at irregularities in grain boundaries and particularly at grain boundary junctions, where the shape of a triple point void is similar to the shape of a stressed crack. Once growth initiation occurs, the crack may follow either an intergranular or transgranular path.

At fast loading rates or under thermal shocks, <u>transgranular cracking</u> dominates. Observations indicate that these cracks are characterizd by the smooth and often striated surface features of cleavage cracks. In addition they often change direction abruptly on intersecting a boundary in order to be parallel or perpendicular to the basal plane. On the other hand at slower loading rates, <u>intergranular cracking</u> tends to dominate. The back stresses associated with anelasticity significantly contribute to the (recoverable) strain energy for crack growth at these rates of deformation. These stresses tend to concentrate on grain boundary planes associated with crystals poorly oriented for deformation, particularly on the soft system. Hence, the preference for intergranular cracking. In addition, the stress required to cause growth initiation (or the stress for crack nucleation) is smaller when anelasticity is present since at any given stress level more elastic strain energy is stored in the material.

The commencement of growth for a single crack does not necessarily lead to material instability if toughening mechanisms are active. Crack deflection at grain boundaries and voids provides one form of toughening. If the applied loading is inadequate to overcome these barriers, further growth of the crack is arrested. This is typically the case under stress states involving pure compression. The length of the arrested cracks is typically several (three) times the grain diameter. The first crack which forms under compressive loading tends to be stable and has been linked to the yield point phenomenon in ice. The material can sustain additional compressive stress beyond the yield point and prior to reaching its ultimate strength. During this additional stressing, multiple stable cracks are formed in the material. This <u>distributed cracking</u> phenomenon governs the ductile-to-brittle transition or purely brittle behavior in ice. This type of cracking weakens ice; under compressive creep stresses the phenomenon leads to "tertiary" or accelerated creep and under constant strain rate loading in compression to "strain softening." At relatively fast rates of loading involving brittle behavior, ultimate failure is by splitting, while in the transition range of loading rates a shear mode of failure dominates. The application of a low to moderate level of confining pressure tends to suppress the development of stable cracks, which in turn allows a higher shear/distortional stress to be sustained (Fig. 9). Ultimate failure generally is in the shearing mode. As the confining pressure is further increased the material displays pressure insensitive ductile flow, and eventually at very high confining pressures pressure-melting is induced and the material can no longer sustain shear/distortional stress. Theoretical models which integrate the flow and damage behavior of ice under multiaxial loading histories are under active development at MIT and elsewhere.

States of stress involving tension typically lead to localized and unstable crack propagation. In ice with grain diameters larger than a critical value (typical of most engineering applications), the first crack which forms (nucleates) propagates in an unstable manner. The stress at which this crack forms defines the tensile strength. On the other hand, when the grain diameter is smaller than the critical value, crack growth is arrested. Additional stress is necessary for unstable crack propagation. Although viscous flow often accompanies ice deformation prior to localization of cracking, it is the elastic energy which is available for the creation of new material surfaces (i.e., fracture energy) that defines the onset of instability.

The energy or stress intensity required for initiating crack growth in ice and for its subsequent unstable propagation are not the same. The crack initiates at a pre-existing defect and then grows along an intergranular or transgranular path. The resistance to its growth is provided by the surface energy (or energies) appropriate for the particular crack path (or paths.) The onset of crack instablility in ice is governed by toughening mechanisms, one of which is crack deflection. Since crack tip plasticity is generally absent in ice, the development of a process zone containing discontiguous cracks can also toughen the material. The amount of toughening clearly depends on the structure and form of the polycrystal. Experimental determination of the critical fracture energy involving such toughening mechanisms is sensitive to specimen geometry and the amount of crack-tip damage introduced when pre-cracking the specimen.

5. Deformation and Failure of Frozen Earth

Many engineering problems in cold regions related to thawing of soils. The freezing of earth may cause frost heaving, a phenomenon of special importance in the temperate zone. Three conditions are required for <u>frost heaving</u> to occur: (1) a cold surface must exist to propagate freezing; (2) a source of water must exist to feed ice growth; and (3) the physical composition of the soil must promote the migration of moisture to the freezing front. When all three conditions are satisfied, free moisture from the earth below migrates along the thermal gradient toward the colder surface on top. The moisture freezes preferentially to existing ice grains when it reaches the frost zone, forming ice lenses. The lenses form normal to the direction of heat flow and are therefore approximately parallel to the ground surface. As these lenses grow and expand, the surface of the earth moves upward. This movement may be non-uniform due to variations in the soil profile, ground water, or surface cover. These total anddifferential movements produce undesirable effects on constructed facilities, especially pavements.

Although the ice segregation process is quite complex, it is known that growth occurs as long as moisture can be attracted from the adjacent soil at the rate of freezing. When the heat removal rate exceeds the moisture supply, the freezing front advances and a new ice lense forms. The total amount of surface heave is often close to the thickness of segregated ice layers in non-compressible earth. Several centimeters of heaving in a single season is common, though much larger magnitudes are not unusual. The temperate and subpolar regions characterized by seasonal frost have greater potential for frost heaving, unlike polar regions with permafrost, due to the almost unlimited availability of free moisture from ground water near the freezing front.

Experimental studies show that particle size provides a valid criterion of <u>frost susceptibility</u> in frozen earth. Although there is no sharp dividing line between frost susceptible and non frost susceptible materials, smaller particles seem to have a dominating influence on the maximum heaving pressures that are developed in a particular material. The rate of heave decreases with increase in pressure. Heaving pressure increases with constraint provided by confining pressure.

Two basic counter measures against frost heaving are available: the first involves earth improvement measures, while the second involves stabilization of constructed facilities. Earth improvement measures include: mechanical techniques such as changes in the composition and density of earth or loads on earth; thermophysical techniques such as changes to the temperature and humidity conditions to control migration of moisture; and physicochemical techniques such as artificial salinization to prevent freezing, introducton of inorganic compounds to change filtration and capillary properties, introduction of less wettable compounds, and electrochemical treatment. Stabilization measures include: improved ground drainage for preventing moisture migration to the freezing front, heating of the earth in constructed facilities to prevent freezing using heat insulating screens or artificial methods of heating, application of counteracting forces, and use of non frost susceptible materials in construction.

Thawing of earth in the active layer causes melting of the pore ice including lenses. As melting progresses downward, the melt water cannot penetrate the frozen earth below and often is unable to dissipate laterally. The trapped water induces excess pore pressures that can drastically reduce the effective strength of the soil. This phenomenon is termed thaw weakening. When consolidation occurs subsequently, pore pressures dissipate and the material recovers part of its strength. Voids are left when the water escapes, increasing the permeability of the soil. The dissipation of excess pore pressures is termed thaw consolidation, while additional dissipation of pore pressures represents ordinary consolidation. Part of the recovery may also be associated with desaturation of the earth. Thawing causes both uniform and differential settlements as well as stability problems in earth masses. The movement of the finer mineral particles together with water on thawing can give rise to serious erosion problems, particularly under repeated loading conditions.

Although some variation in the permafrost table can occur due to changes in the natural weather pattern, larger shifts are caused by modifications to the surface cover or introduction of artificial heating sources. In ice rich earth, the potential for settlement associated with the thawing of permafrost is substantial.

The initial effective stress in earth thawed under undrained conditions governs the magnitude of settlements in the earth. When the effective stress is high, the subsequent consolidation settlements and pore pressures generated during thaw are smaller while the undrained shear strength is higher.

Three major principles of construction are available for dealing with frozen earth. They are: (1) to preserve the frozen state of the ground; (2) to design for settlements due to thawing ground; and (3) to improve the ground by pre-construction thawing. The first principle is appropriate in the polar and extreme latitudes of the subpolar zones and when the constructed facilities do not release substantial amounts of heat and do not occupy large areas. Methods for preserving the frozen state of earth attempt to remove heat. One approach is to provide ventilation between the heat source and the frozen earth through physical separation. A second approach involves the use of special pipes with natural or forced ventilation or coarse-pored ventilated rock fill between the heat source and frozen earth. Artificial cooling of thaw susceptible soils may also be considered. The second principle requires a predictive theory of settlements in thawing earth. If the settlements are excessive, an alternative principle must be adopted. The last principle is adopted when it is necessary to reduce (a) future settlements due to thawing and thawed earth, (b) differential settlements in earth of highly non uniform compressibility in the frozen and thawed states, and (c) where the frozen soil is discontinuous in the horizontal direction. Pre-construction thawing methods rely on natural solar heat or on artificial heat sources. Examples of artificial heat sources include: hydraulic sources such as hot and cold water; steam; electric heating with alternating current; and thermochemical methods. Pre-construction thawing can be augmented by mechanical methods for compacting and artificially strengthening the earth.

Frozen ground, particularly permafrost, is both stable and strong due to the presence of ice-cement bonds. However, the stresses and strains in frozen earth vary with time when loaded since the ice cement and ice interlayers flow. Thus frozen earth displays creep, stress relaxation and recovery behavior. When the degree of ice saturation is large, the mechanical behavior may approximate that for ice, with a very small long term strength. On the other hand when the degree of ice saturation is small, the interparticle forces may dominate leading to a mechanical behavior similar to unfrozen soil. But most permafrost exists between these two extremes, leading to a very complex and poorly understood interaction between the mineral soil skeleton and the crystalline ice in the pores.

Two general approaches exist for predicting the deformation and compressibility of frozen earth: (a) consider frozen earth to be a quasi-single-phase medium with mathematically well defined properties, neglecting the fact that one portion of the deformation is due to volume changes; or (b) consider consolidation and flow as two simultaneous but separate phenomena, whose relative amounts o_ deformation depend on the applied loads and elapsed time. The first approach is easier and more practical, while the second approach is complex but more rigorous. However, in general, the consolidation component of deformation can be neglected in most practical problems.

Creep deformation of frozen soil can be divided into three stages: primary or transient creep, secondary creep or steady flow, and tertiary or accelerating creep (Fig. 10). The primary stage is characterized by the closure of microcracks, healing of structural defects by moisture that has been pressed out of overstressed zones and refrozen, a decrease in free porosity due to particle dislocation, and partial closure or size reduction of macrocracks. All of these factors cause rheological compacting of the frozen earth. Compressibility of frozen earth can be neglected during primary creep, although the actual amount depends on the pressure. Creep is considered to take place at a constant volume with the soil particles being slowly rearranged in the ice matrix. Some compressibility may occur due to compression of the gaseous phase, creep of the ice-cement due to shear stresses at the grain contacts, and hydrodynamic consolidation due to the redistribution of unfrozen water under stress. The transition from primary creep to secondary creep occurs at a single point on a creep curve and is characterized mainly by microscopic cracking. Essentially incompressible secondary creep results when equilibrium is established between healing of existing structural defects and the generation of new defects. In effect secondary creep is a point of inflection on the creep curve. Finally, during tertiary creep new microcracks are generated at an increasing rate which eventually develop into macrocracks. In addition, the recrystallization and reorientation of ice inclusions causes a decrease in their shear resistance and, consequently, of the frozen earth. In practical applications, it is often sufficient to consider only primary creep in ice-poor earth and for ice-rich soils secondary creep can be used as an approximate representation of creep behavior; especially for frozen silts and clays.

6. Sources of Information

The bibliographic references at the end of this article are a valuable source of information on ice and frozen earth. In addition several scientific journals and international conferences, listed below, emphasize the study of these materials.

<u>Scientific Journals</u>:

- Annals of Glaciology
- Canadian Geotechnical Journal
- Cold Regions Science and Technology
- Journal of Glaciology
- Journal of Offshore Mechanics and Arctic Engineering

<u>Proceedings of International Conferences</u>:

- IAHR Symposium on Ice

International Permafrost Conference
International Symposium on Ground Freezing (ISGF)
Offshore Mechanics and Arctic Engineering (OMAE)
Port and Ocean Engineering Under Arctic Conditions (POAC)

The article by E.M. Schulson entitled "The Mechanical Properties of Ice: An Overview" in a companion volume of the Encyclopedia of Materials Science and Engineering provides a different, but complementary, perspective on the topic of ice. The books by Tsytovich (1975) and Andersland and Anderson (1978) listed in the bibliography have significantly influenced the discussion on frozen earth contained in this article.

Acknowledgements

The author is grateful to F.H. Sayles, W. Quinn and A. Fish of the U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, and C.C. Ladd of MIT for comments and suggestions on an initial draft of the manuscript.

Bibliography

Andersland O B, Anderson D M 1978 Geotechnical Engineering for Cold Regions. McGraw-Hill, New York, NY.

Ashton G D 1986 River and Lake Ice Engineering. Water Resources Publications, Littleton, CO.

Barnes P, Tabor D, Walker J C F 1971 The Friction and Creep of Polycrystalline Ice. Proceedings Royal Society, London A. 324: 127-155.

Chamberlain E J 1981 Frost Susceptibility of Soil: Review of Index Tests. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH: Monograph 81-2.

Chung J S, Hallam S D, Maatanen M, Sinha N K, Sodhi D S 1987 Advances in Ice Mechanics - 1987. American Society of Mechanical Engineers, New York, NY: International Offshore Mechanics and Arctic Engineering Symposium Committee, 49p.

Eranti E, Lee G C 1986 Cold Region Structural Engineering. McGraw-Hill, New York, NY.

Farouki O T 1981 Thermal Properties of Soils. U.S. Army Cold

Regions Research and Engineering Laboratory, Hanover, NH: Monograph 81-1.

Fish A M 1984 Thermodynamic Model of Creep at Constant Stress and Constant Strain Rate. Cold Regions Science and Technology. 45:143-161.

Gandhi C, Ashby M F 1979 Fracture-Mechanism Maps for Materials which Cleave: F.C.C., B.C.C. and H.C.P. Metals and Ceramics. Acta Metallurgica. 27: 1565-1602.

Glen J W 1975 The Mechanics of Ice. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH: Monograph 11-C 2b.

Gold L W 1963 Crack Formation in Ice Plates by Thermal Shock. Canadian Journal of Physics. 41: 1712-1728.

Goodman D J, Frost H J, Ashby M F 1981 The Plasticity of Polycrystalline Ice. Philosophical Magazine A. 43(3): 665-695.

Hobbs P V 1974 Ice Physics. Clarendon, Oxford.

Johnston G H (ed.) 1981 Permafrost Engineering Design and Construction. John Wiley, Toronto.

Ketcham W M, Hobbs P V 1969 An Experimental Determination of the Surface Energies of Ice. Philosophical Magazine, Eighth Series. 19(162): 1161-1173.

Mellor M 1983 Mechanical Behavior of Sea Ice. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH: Monograph 83-1.

Michel B 1978 Ice Mechanics. University of Laval Press, Quebec City.

Schulson E M 1987 The Mechanical Properties of Ice: An Overview. In: Cahn R (ed.) Advances in Materials Science and Engineering, Pergamon, Oxford.

Shyam Sunder S, Wu M S 1988 A Multiaxial Differential Flow Law for Polycrystalline Ice. Cold Regions Science and Technology.

Ting J M, Martin R T, Ladd C C 1983 Mechanisms of Strength for Frozen Sand. Journal of Geotechnical Engineering. 109(10): 1286-1302.

Tsytovich N A 1975 The Mechanics of Frozen Ground. Scripta Book Company, Washington DC.

Vyalov S S, Gmoshinskii V G, Gorodetskii S E, Grigorieve V G, Zaretski I K, Pekarskaia N K, Shusherina E P 1962 The Strength and Creep of Frozen Soils and Calculations for Ice-Soil Retaining Structures. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH: Translation No. 76, 1965.

Weeks W F and Ackley S F 1982 The Growth, Structure, and Properties of Sea Ice. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH: Monograph 82-1.

Weertman J 1983 Creep Deformation of Ice. Annual Review of Earth and Planetary Science. 11:215-240.

S. Shyam Sunder
Massachusetts Institute of Technology

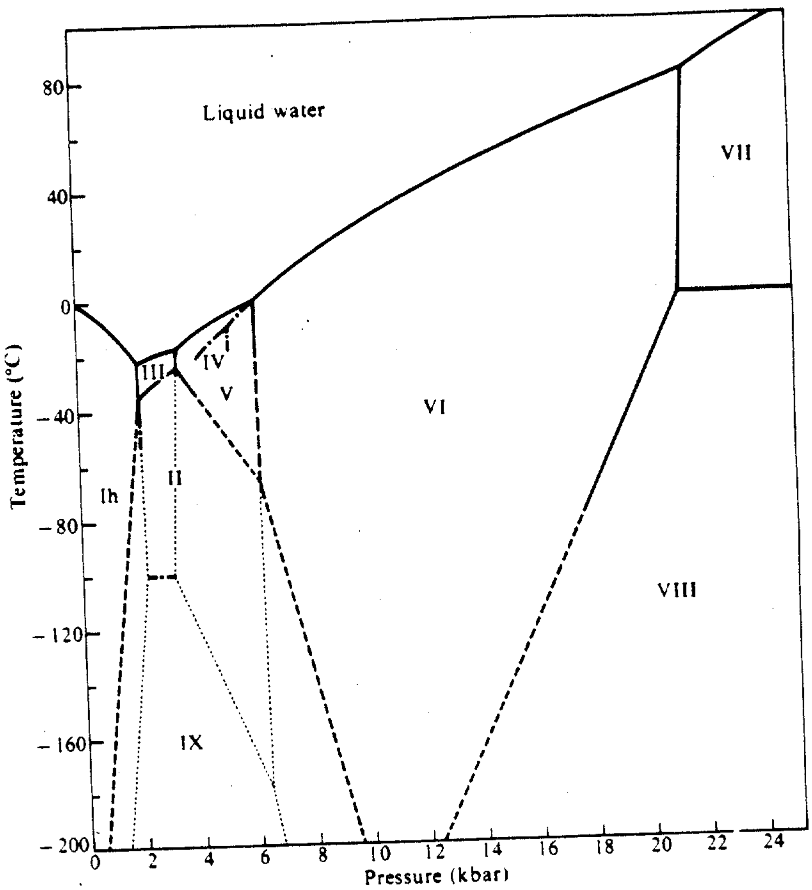

Figure 1. Phase Diagram of the Solid Phases of Water (after Hobbs 1974. <u>Ice Physics</u>, Clarendon, Oxford.)

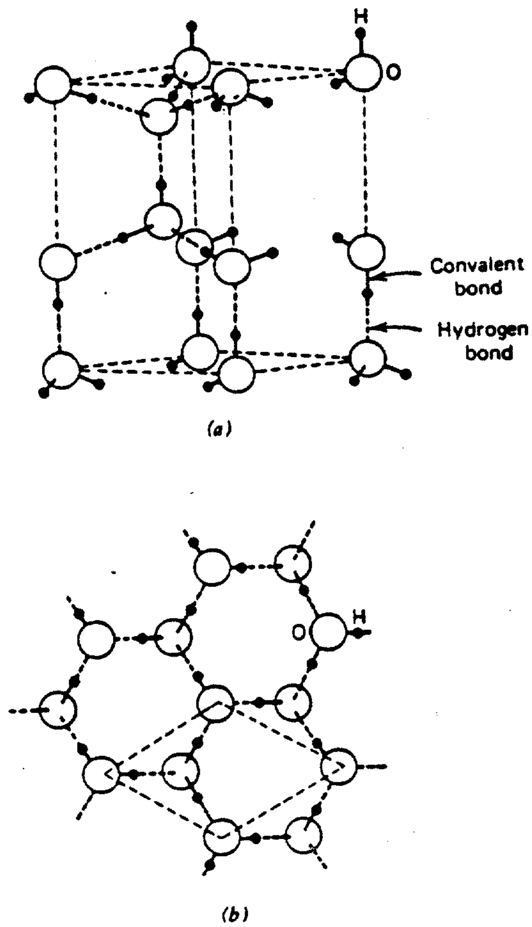

Figure 2. Model of an Ice Crystal. As Shown in the Perspective Representation (a), Each Oxygen Atom is Coupled to Two Hydrogen Atoms in Other H_2O Molecules by Hydrogen Bonds. In (b), the Hexagonal Symmetry of Ice is Shown. Hydrogen Bonds are Indicated as (-----) and Covalent Bonds, as (———).

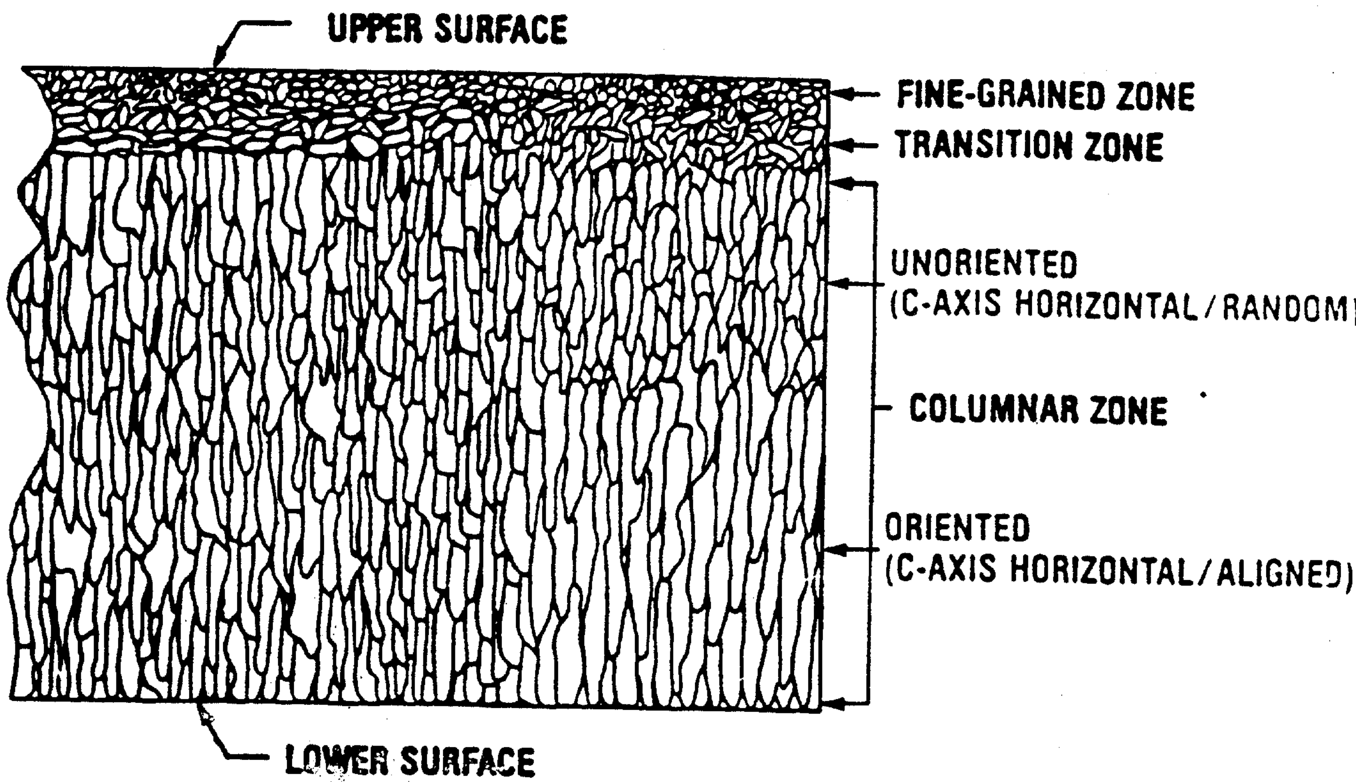

Figure 3. Crystal Structure of a Typical Arctic Sea Ice Sheet.

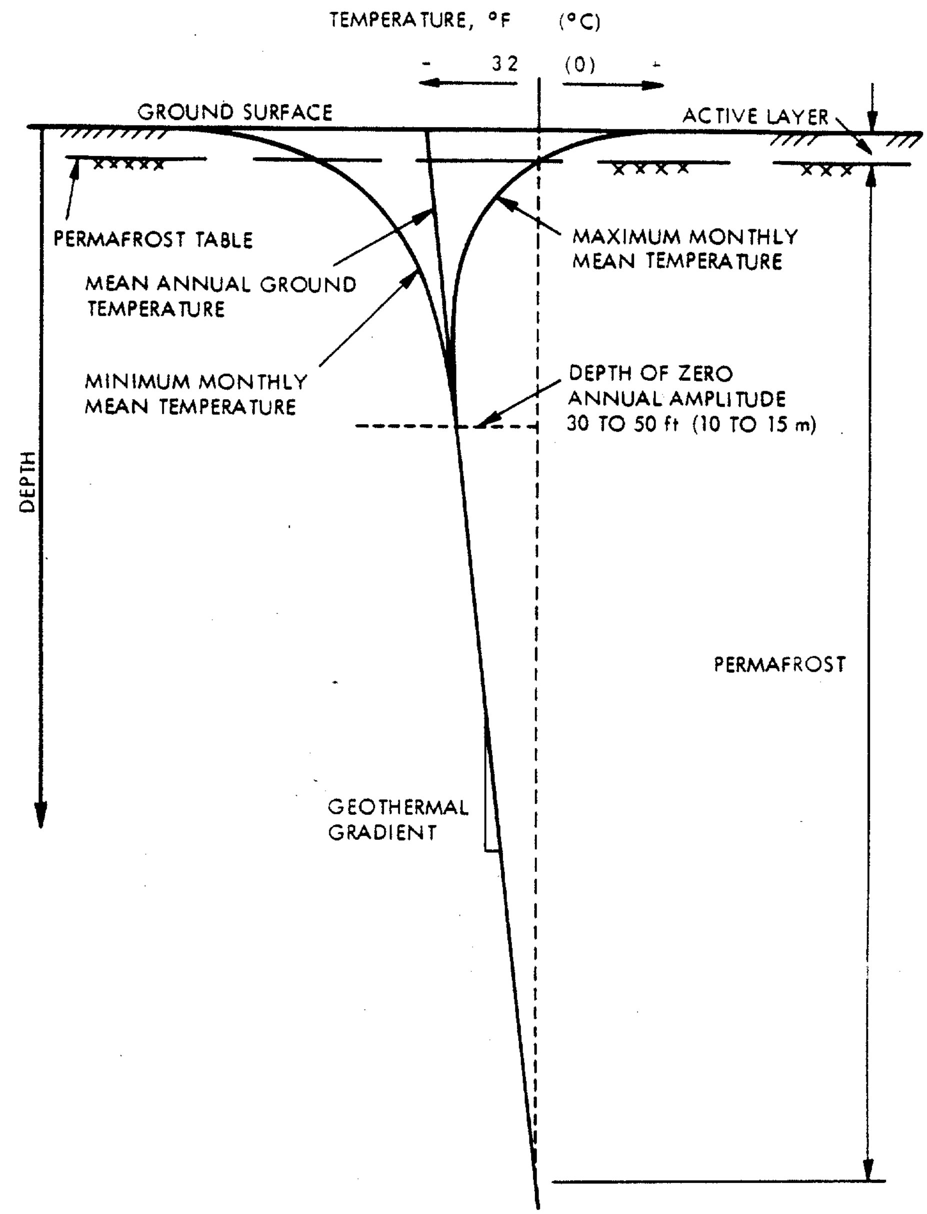

Figure 4. Typical Ground Temperature Regime in Permafrost.

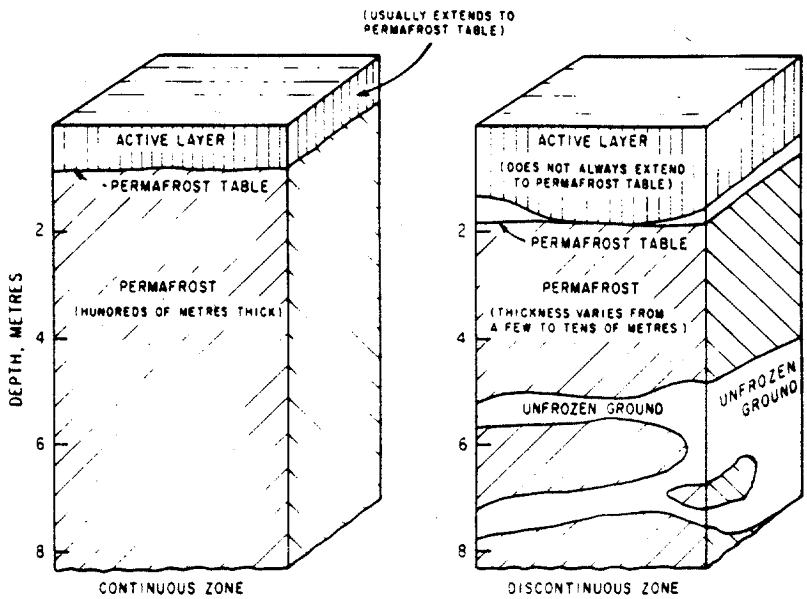

Figure 5. Typical Profiles of Permafrost Distribution.

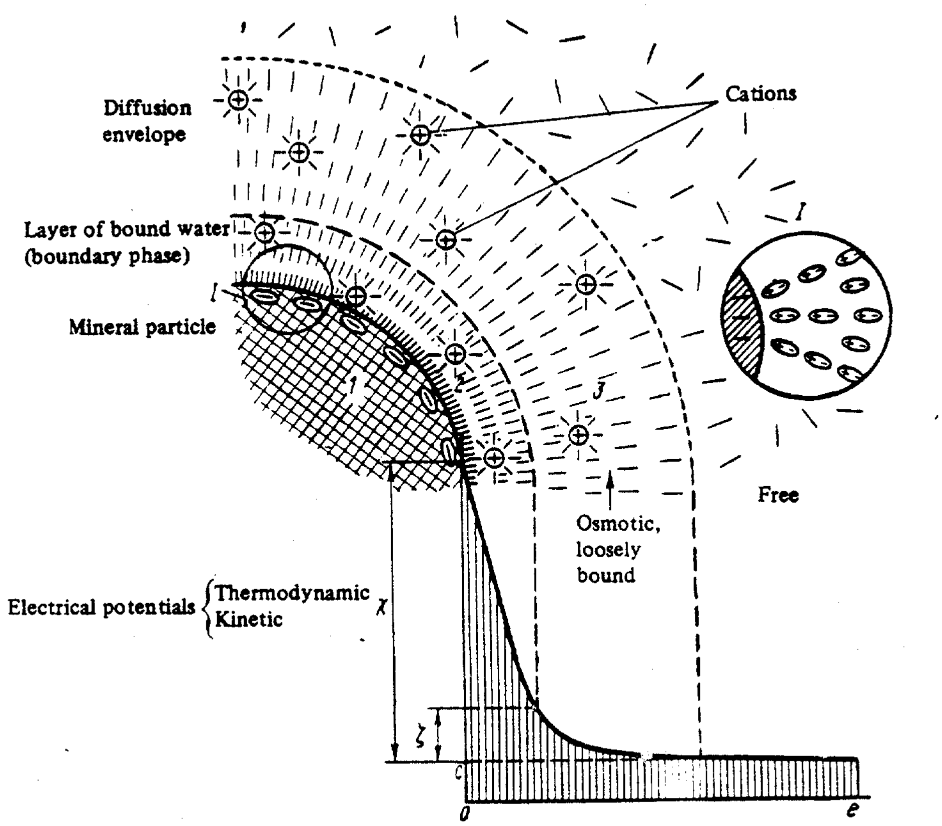

Figure 6. Schematic of Electromolecular Interaction of the Surface of a Mineral Particle with Water: (1) Mineral Particle; (2) Bound Water; (3) Loosely Bound (Osmotic) Water. (after Tsytovich 1975. The Mechanics of Frozen Ground, Scripta Book Company, Washington, D.C.)

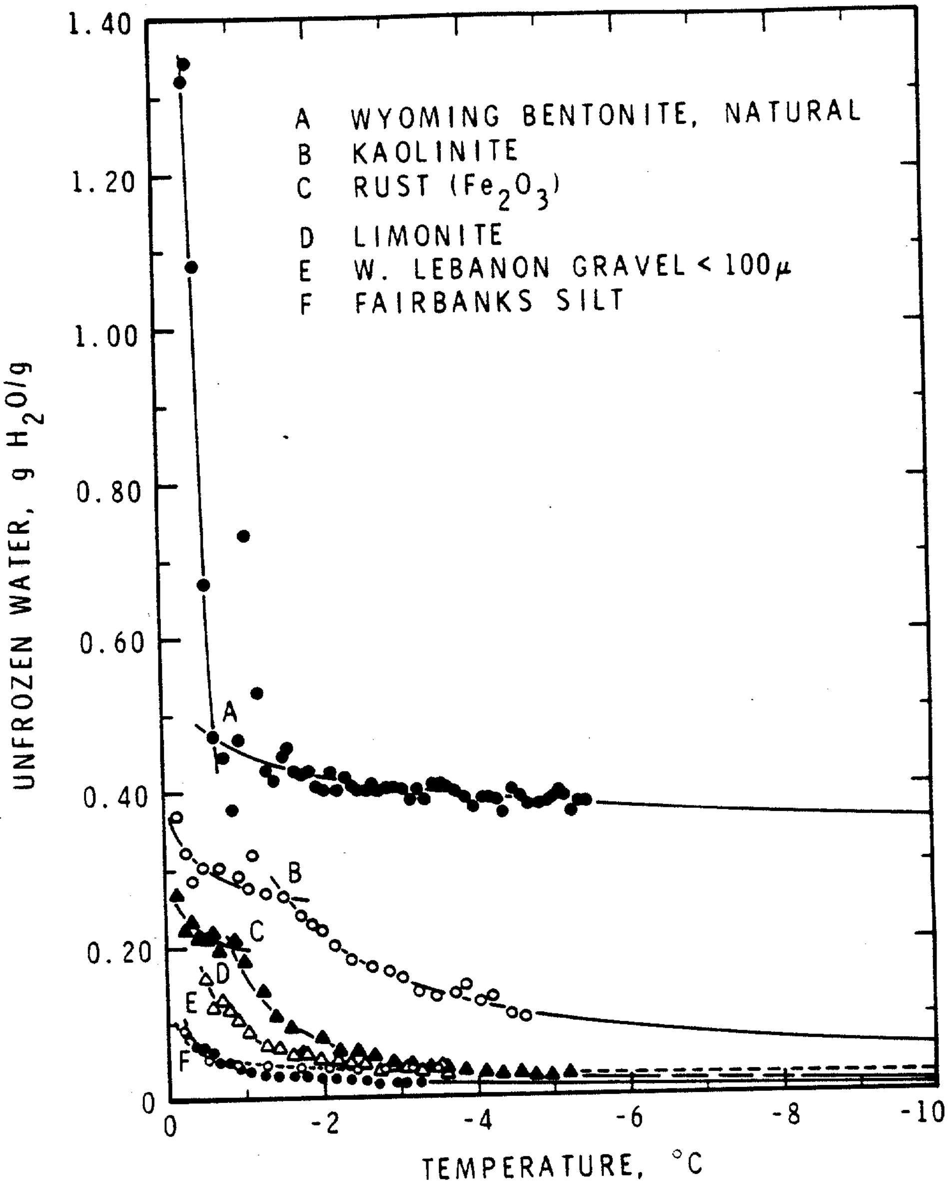

Figure 7. Variation of Unfrozen Water Content with Temperature for Six Representative Soils and Soil Constituents (after Anderson and Morgenstern 1973. Physics, Chemistry and Mechanics of Frozen Ground: A Review, Proc. 2nd International Conference on Permafrost, Yakutsk, U.S.S.R., North American Contribution, U.S. National Academy of Sciences, pp. 289-295.)

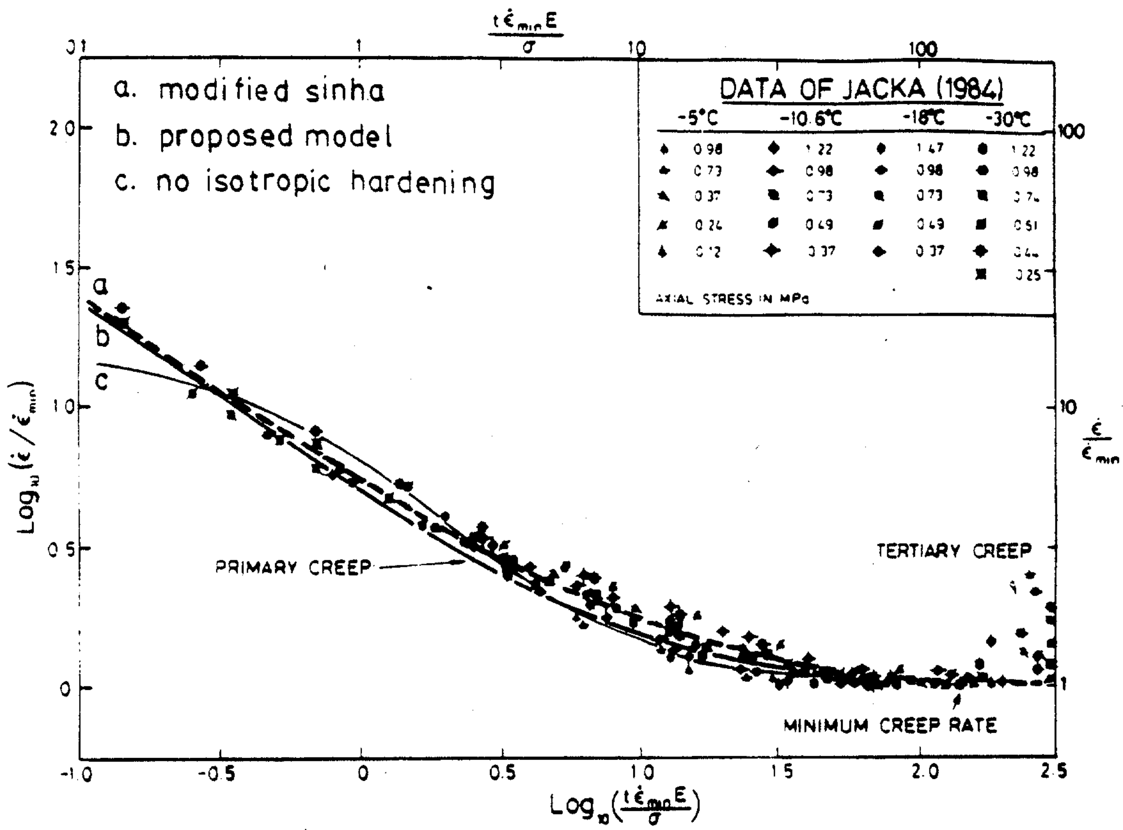

Figure 8. Dimensionless Strain Rate Versus Dimensionless Time for Isotropic Polycrystalline Ice (after Shyam Sunder and Wu 1988. A Multiaxial Differential Flow Law for Polycrystalline Ice, <u>Cold Regions Science and Technology</u>, Submitted for Publication.)

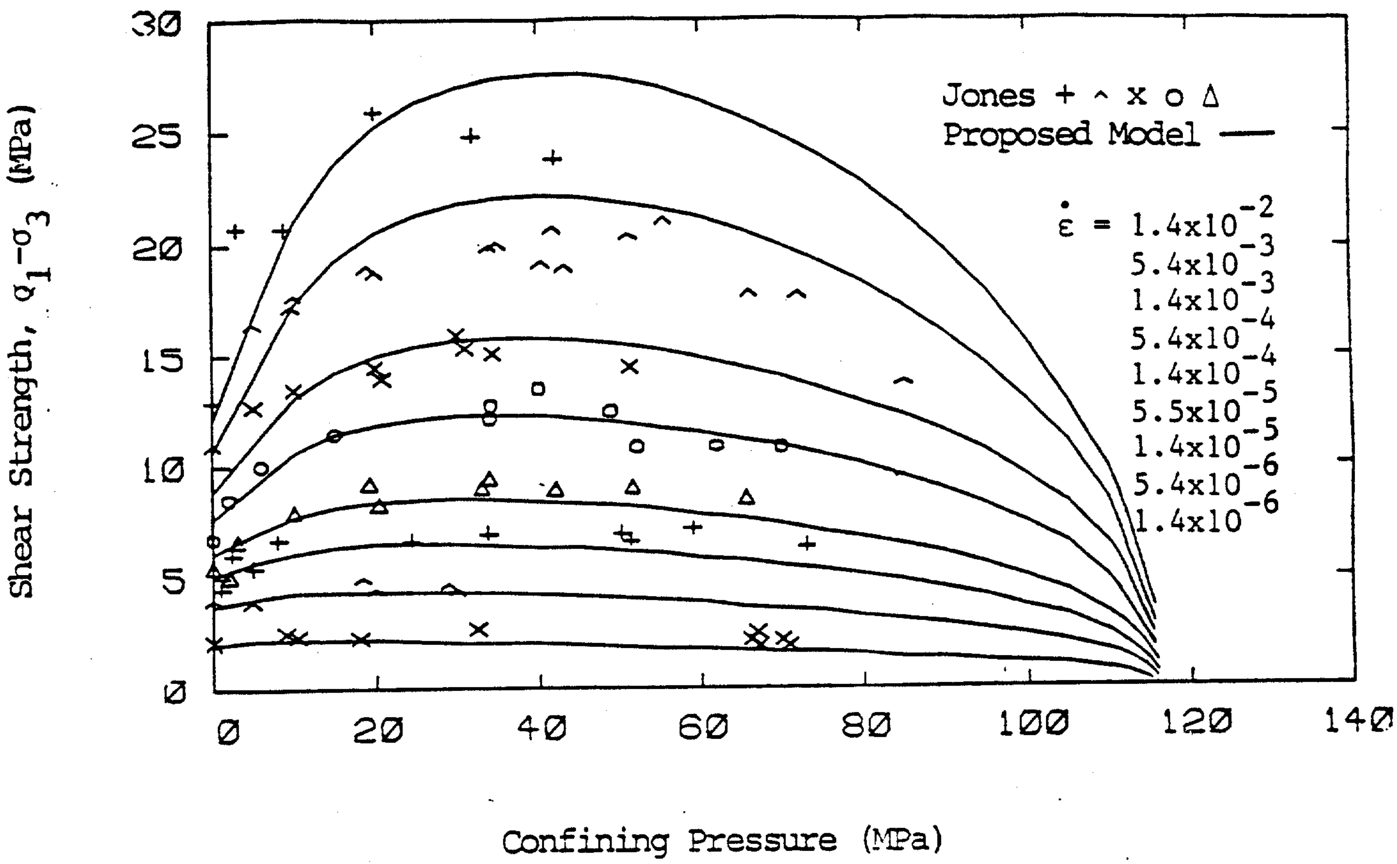

Figure 9. Shear Strength versus Confining Pressure for Freshwater Ice at -12°C (after Wu and Shyam Sunder 1988. A Rate and Pressure Sensitive Damage Model for Polycrystalline Ice, In Preparation.)

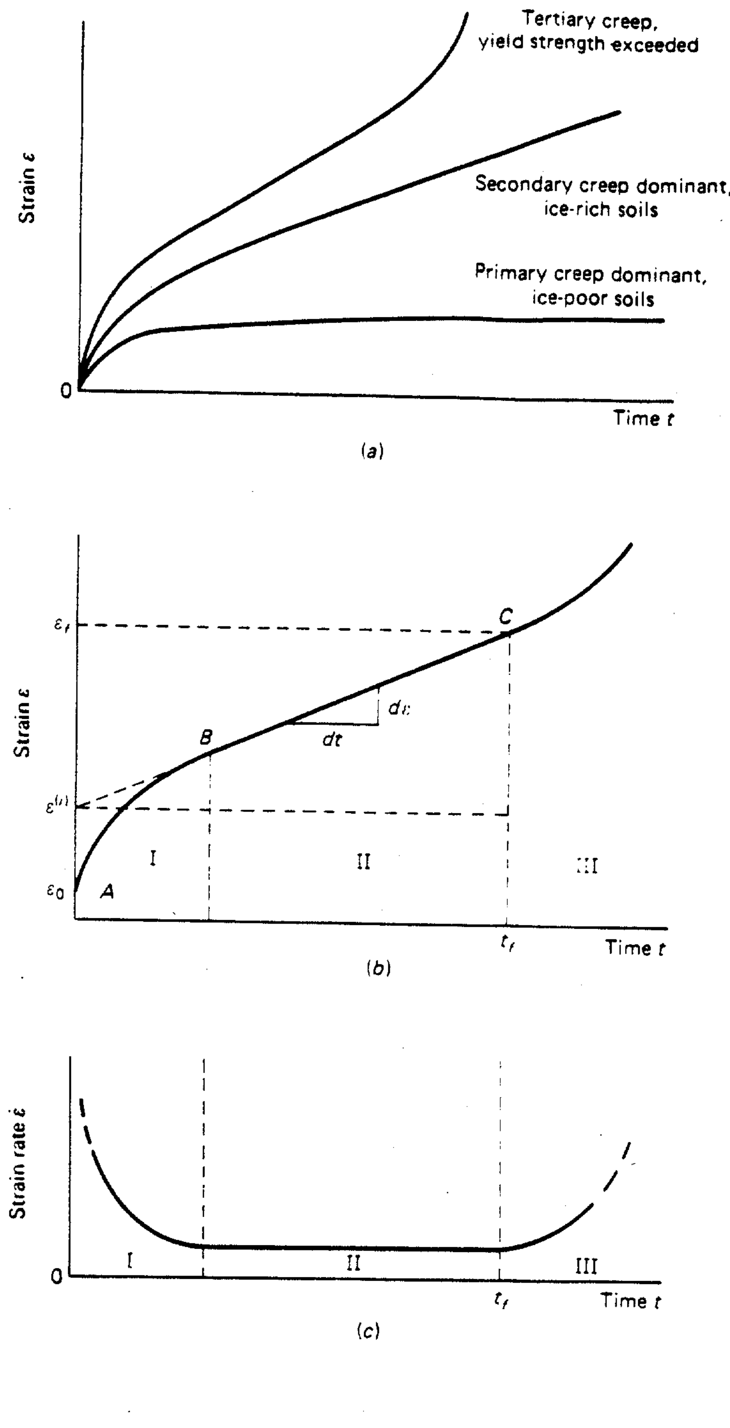

Figure 10. Constant-Stress Creep Test: (a) Creep-Curve Variations; (b) Basic Creep Curve; (c) True Strain Rate versus Time.